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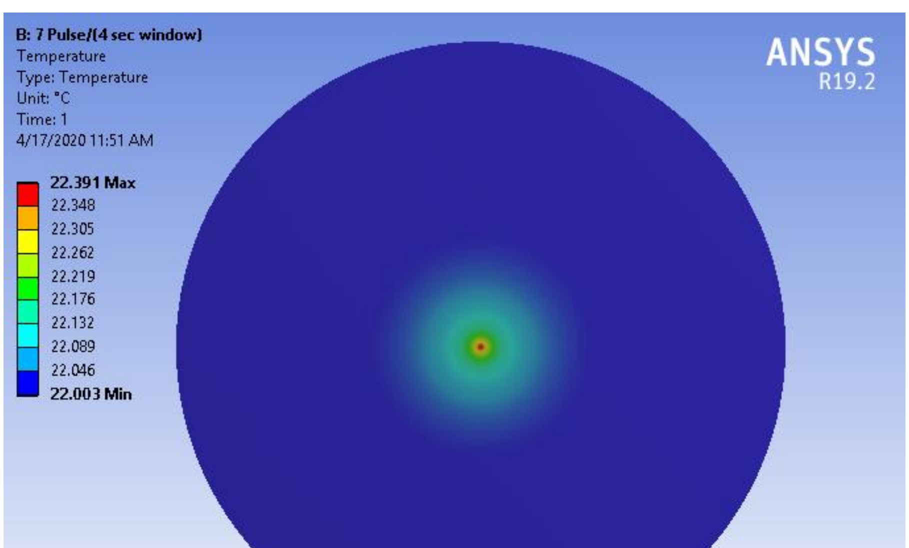
MSD/AD

Thermal Analysis of Grade 5 Ti-6Al-4V 3.625" Aperture Vacuum Window

EN04138



1.0 Introduction

MTA enclosure for ITA (Irradiation Test Area) plans to irradiate detectors to validate functionality in high radiation environments. MTA/ITA has the unique ability to test detectors with a high energy proton beam. In this beamline, exists a 0.002” thick 3.625” aperture vacuum window. The note for the structural integrity of this window can be found under EN01668 in Teamcenter. This note validated the strength of the window under room temperature conditions. The purpose of this note is to verify that the temperature rise in the window does not degrade the mechanical properties of the Ti film (Grade 5 Ti-6AL-4V) so much that it can no longer withstand the pressure difference between vacuum and atmosphere (roughly 14.7 psi)

Two operating conditions were considered for this note:

1. Window experiences 7 pulses of beam in a 4 second window.
    a. Under this condition, the analysis assumes the cycle of 7 pulses every 4 seconds continues resulting in 105 pulse/minute.
    b. NOTE: Under normal operating conditions the window will experience 7 pulses of beam every minute. All 7 pulses in a 4 second window is the worse-case in normal operation. The above is 105 pulse/minute is chosen to be conservative.
2. Window experiences all 900 pulses/minute of beam.

The two cases for steady state thermal above will be followed up by a transient thermal analysis to confirm that the maximum local temperatures during beam pulses do not cause structural degradation.

2.0 Steady State Thermal Analysis

The objective of this analysis is to use given beam power parameters to create a conservative estimate for power delivered to a spot size on the Ti film and determine the steady state temperature profile of the film for a particular set of heat transfer constraints. The beam power is modeled as internal heat generation in the volume of the film’s spot size. This spot is a circular gaussian area where the beam is interacting with the film. The film is the only body analyzed and is the shape of a 0.002” tall cylinder with a diameter of 3.625”. This cylinder is insulated on all sides except the one side that is exposed to room temperature at atmospheric pressure. Though conduction will exist on connecting structures, they are ignored along with any radiation to be conservative and simplify the model.

Below are the calculations for the approximation of the two cases of beam power with the given beam parameters. Also, a link to Adam Watts report which the equations used for determining beam power were taken.

Beam power given number of particles (n), proton charge (q_p), kinetic energy of beam (K_p) and time (t):

$$P_{beam} = \frac{E}{t} = \frac{nq_pK_p}{t}$$

Fractional interaction length given length of interaction (L) and nuclear interaction length (L_{NI}):

$$L_{frac} = \frac{L}{L_{NI}}$$

Beam loss ratio given fraction interaction length (L_{frac}):

$$\eta = 1 - e^{-L_{frac}}$$

Beam loss (absorbed by our Ti film) given beam power and beam loss ratio:

$$P_{loss} = \eta P_{beam}$$

https://beamdocs.fnal.gov/AD/DocDB/0049/004994/005/effects-rough-vacuum.pdf

Below is the calculation for 400 MeV proton beam power at 15 Hz and Power lost in 0.002 inches of Ti. L_{NI} for Ti can be found here (http://pdg.lbl.gov/2019/AtomicNuclearProperties/HTML/titanium_Ti.html). L_{NI} for Ti is 27.80 cm but to be conservative "Radiation Length" was chosen which is 3.560 cm.

$$P_{beam} = \frac{E}{t} = \frac{nq_pK_p}{t} = \frac{(5.65E12\ protons)(1.602E-19\ C)(400\ MeV)}{\left(\frac{1}{15\ s^{-1}}\right)} = 5430.78\ W$$

$$L_{frac} = \frac{L}{L_{NI}} = \frac{0.002\ in \times 2.54\frac{cm}{in}}{3.56\ cm} = \frac{5.080E-03\ cm}{3.56\ cm} = 1.427E-03\ cm$$

$$\eta = 1 - e^{-L_{frac}} = 1 - e^{-1.427E-03} = 1.426E-03$$

$$P_{loss} = \eta P_{beam} = (1.426E-03)(5430.78W) = 7.744\ W$$

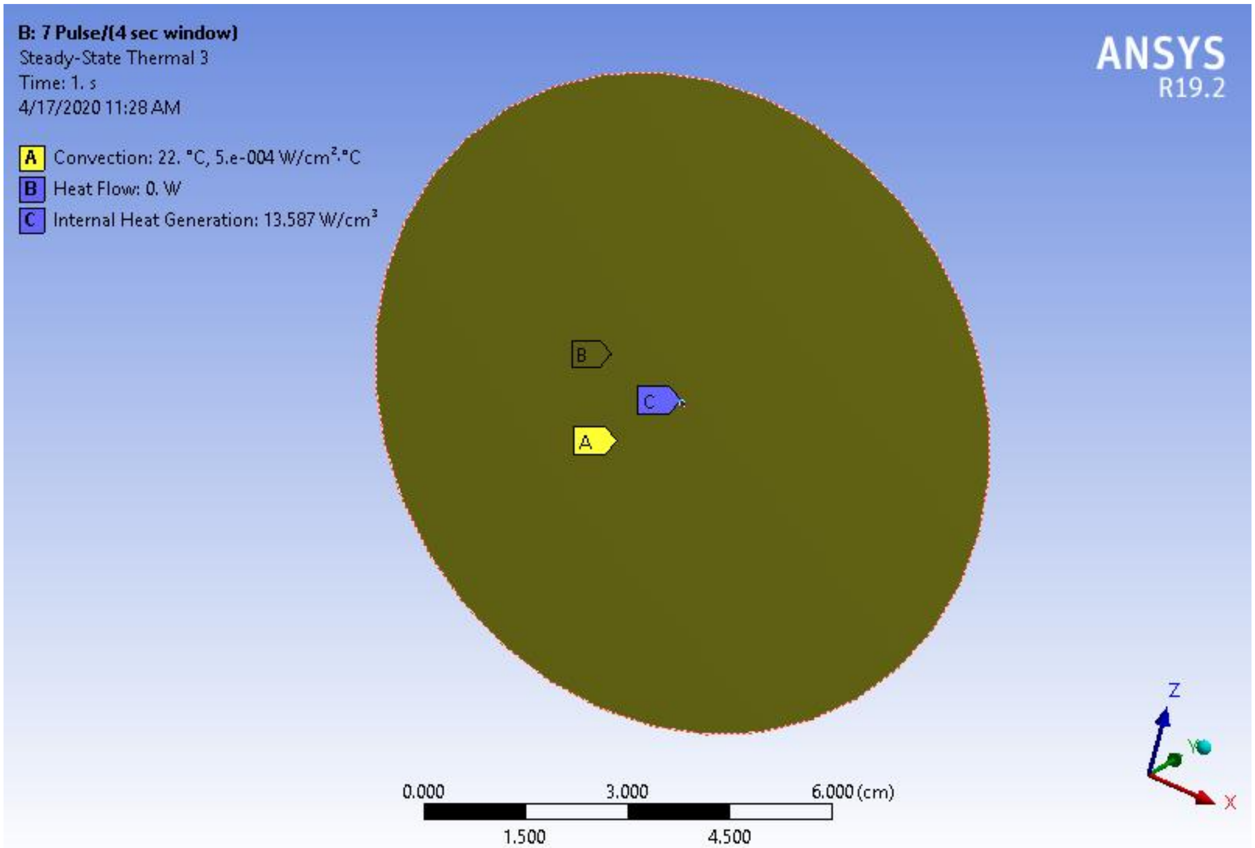
Assuming a spot size with a radius r = 0.05 cm, and thickness t = 0.002 in (5.080E-04 cm), then the spot volume is:

$$V = \pi t r^2 = \pi(5.080E-03\ cm)(0.05\ cm)^2 = 3.990E-05\ cm^3$$

Analysis was done using ANSYS's steady state thermal module. The control system is the entire Ti film. The boundary conditions for the thin film (very thin cylinder) are insulated on all sides but one. The one side is given free convection cooling using the lower end of air's heat transfer coefficient, which is 5

W/m·K. The spot size volume is modeled as the internal heat generator. The heat is allowed to spread to the rest of the film body.

Below is an image of the ANSYS set up:



Below are the calculations for determining the internal heat generation value applied to the spot volume:

Case 1: 7 pulse / 4 seconds = 105 pulses/minute of 400 MeV proton beam.

Each pulse duration is approximately 40 μs, then the energy of one pulse is:

$$E_{1\,pulse} = tP_{loss} = (40\mu s)(7.744W) = 3.098E-04\,J$$

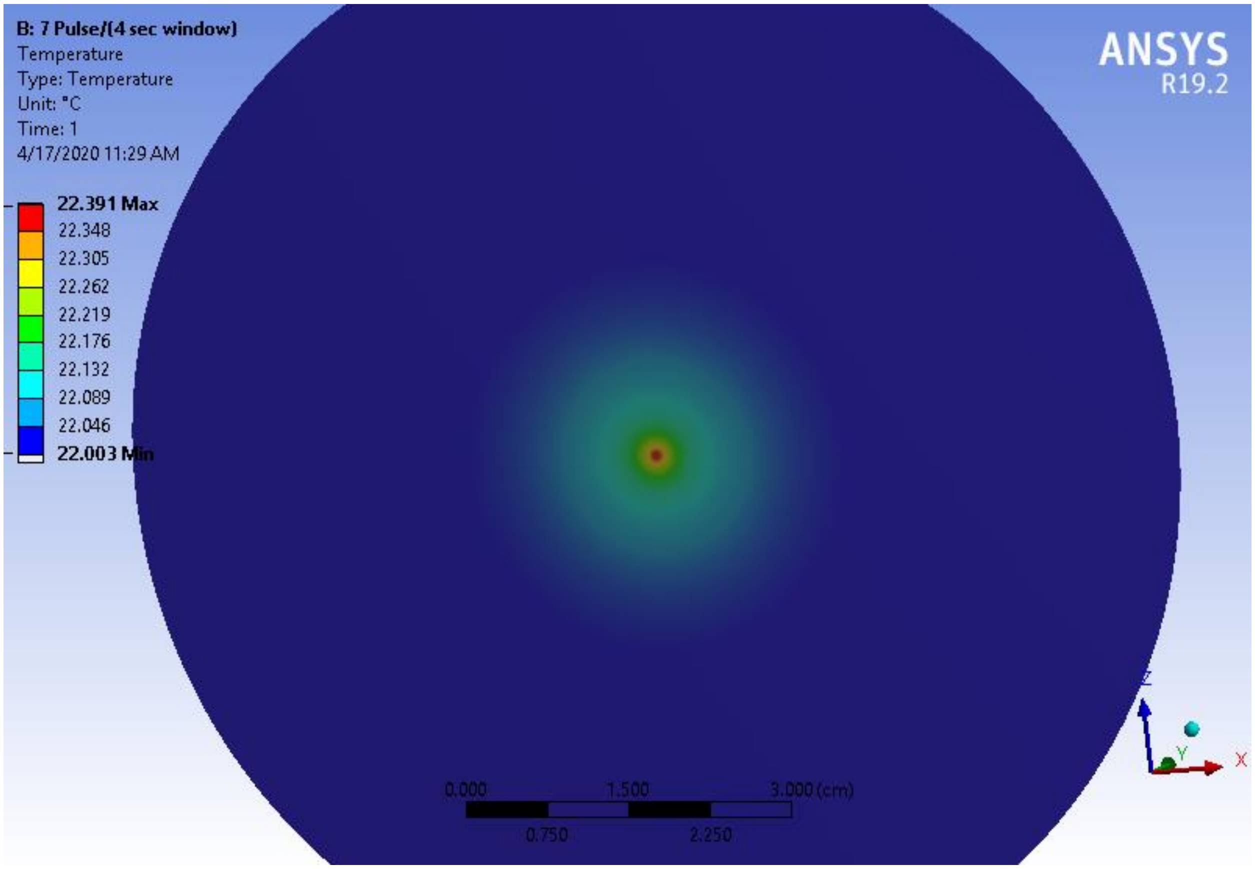
If 7 of these pulses, equally spaced, occur in a 4 second window then the average power is:

$$P_{ave,7} = E_{1\,pulse}\frac{7\,pulses}{4\,s} = (3.098E-04\,J)\frac{7\,pulses}{4\,s} = 5.421E-04\,W$$

Then the internal heat generated by that spot volume due to absorbed beam power is:

$$Q_{ave,7} = \frac{P_{ave,7}}{V} = \frac{5.421E-04\,W}{3.990E-05\,cm^3} = 13.587\frac{W}{cm^3}$$

The ANSYS results below show a steady state temperature profile of the Ti film given the above inputs:



Steady State temperature profile of Ti film given 7 pulses per 4 second (105 pulses / minute) window with convection only.

Case 2:

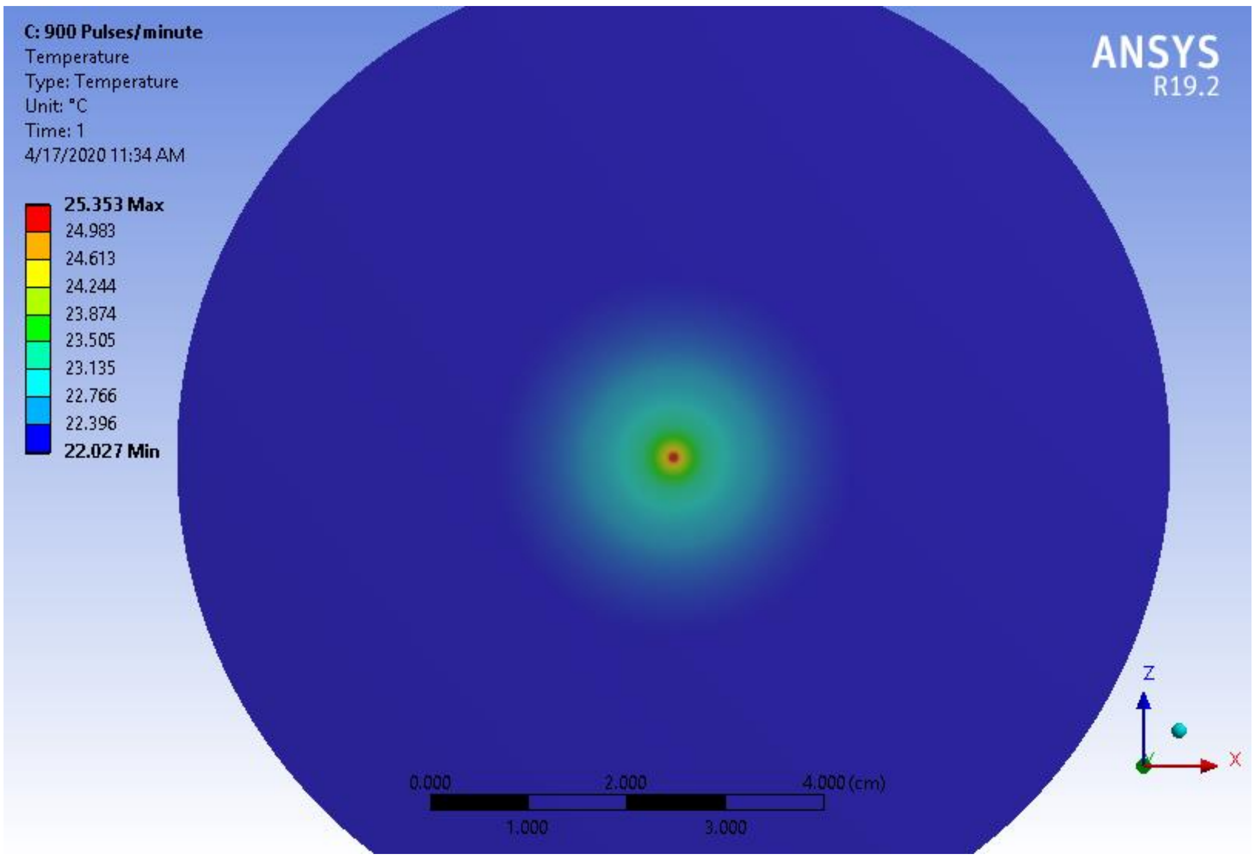
If 900 of these pulses, equally spaced, occur in a 60 second window then the average power is:

$$P_{ave,900} = E_{1\ pulse} \frac{900\ pulses}{60\ s} = (3.098E-04\ J)\frac{900\ pulses}{60\ s} = 4.646-03\ W$$

Then the internal heat generated by that spot volume due to absorbed beam power is:

$$Q_{ave,7} = \frac{P_{ave,900}}{V} = \frac{4.646E-03\ W}{3.990E-05\ cm^3} = 116.457 \frac{W}{cm^3}$$

The ANSYS results below show a steady state temperature profile of the Ti film given the above inputs:



Steady State temperature profile of Ti film given 900 pulses per minute window with convection only.

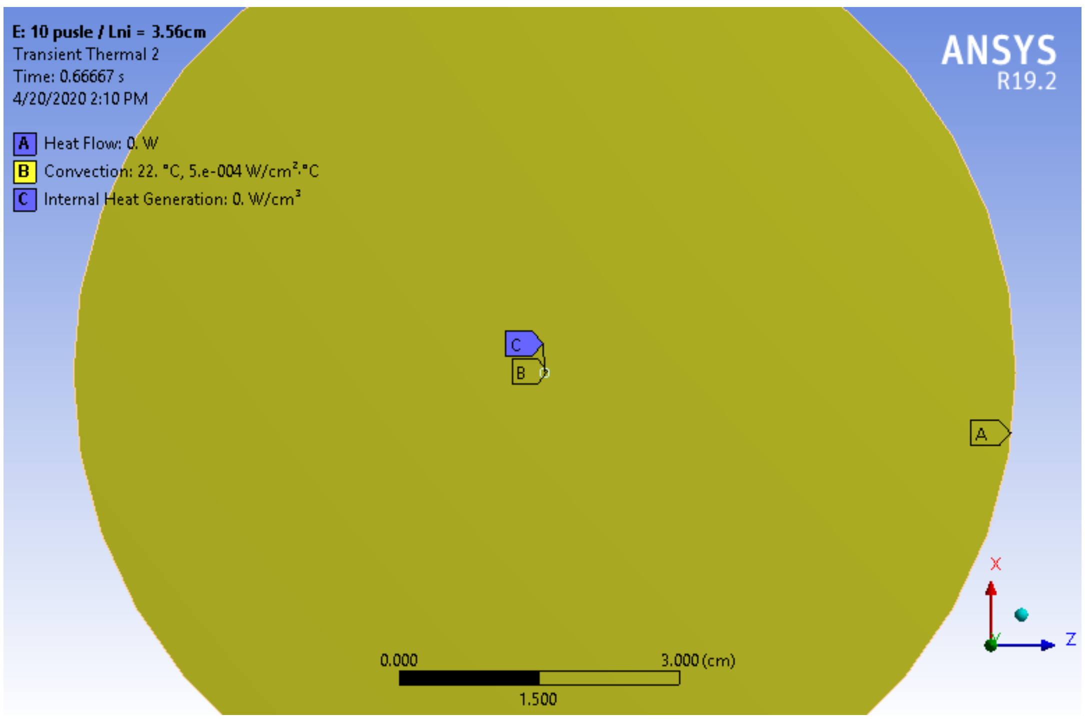
3.0 Transient Thermal Analysis

The same geometry and beam energy from the previous section is used to determine the maximum temperature of the vacuum window during ten pulses of beam.

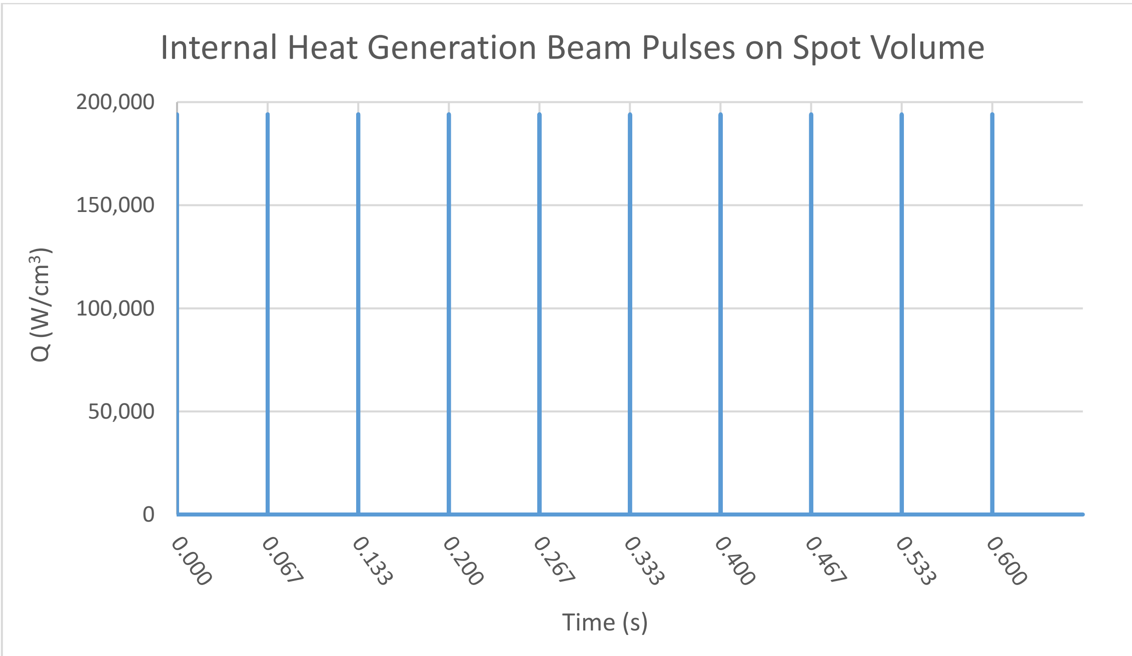
The internal heat generation applied to the spot volume is:

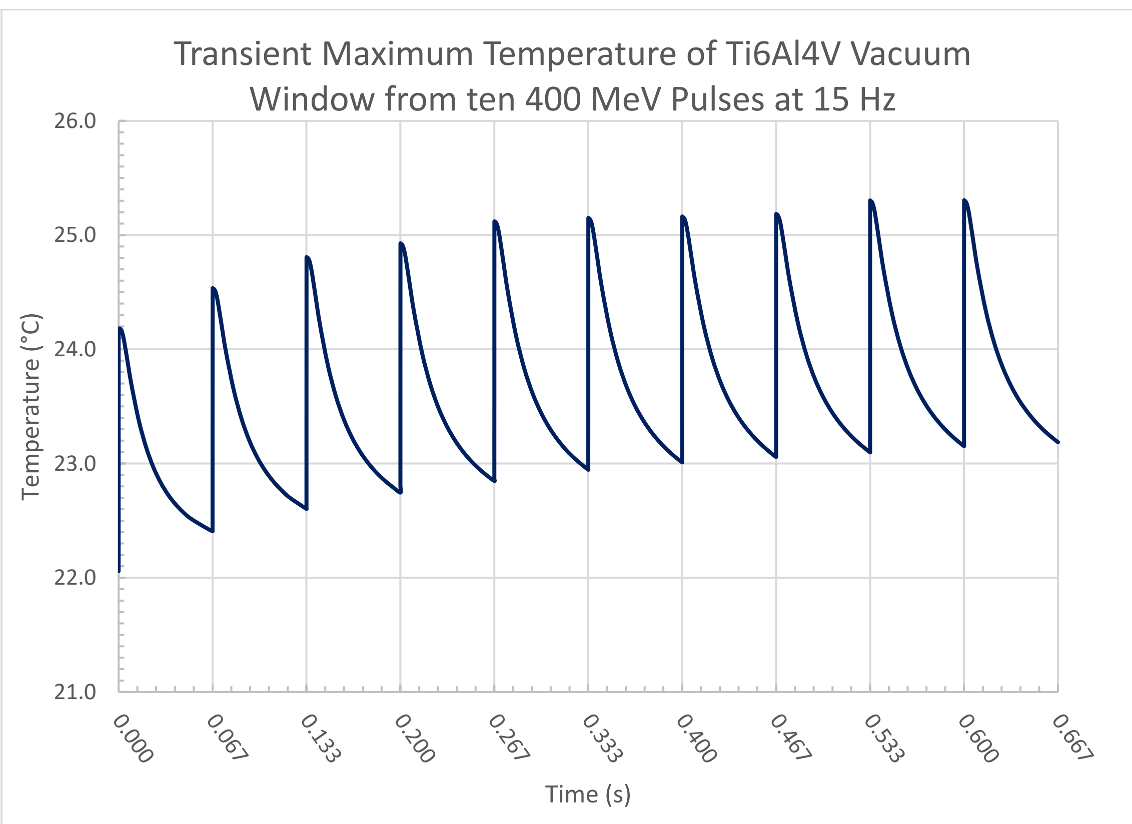
$$Q = \frac{E_{1\,pulse}}{t_{1\,pulse} \times V} = \frac{3.098E - 04\,J}{(40E - 6\,s) \times (3.990E - 05\,cm^3)} = 194{,}110.3\,\frac{W}{cm^3}$$

Q is applied for a duration of 40 µs at 15 Hz (every 0.06667 seconds). This is a more accurate representation of the energy applied to the vacuum window. In the previous section, Q was calculated as an average value over time. Below is an image of the ANSYS setup with the same constraints as steady state analysis in the previous section except for internal heat generation which was given tabulated values to represent the pulsing of the beam on the spot volume.



There are two graphs below. The first one shows Q applied to the spot volume for ten pulses of beam over time. This represents the beam pulses on the vacuum window. The second graph shows the maximum temperature resulting from Q applied to the spot volume.





Based on the above results, there is no concern with instantaneous local maximum temperatures on the spot volume to cause a degradation in the window's structural capability. The temperature rise from 10 pulses of beam at 15 Hz is less than 4°C. The vacuum window will function as noted in EN01668 because the temperature rise is not high enough to change the strength of the Ti-6Al-4V vacuum window.

4.0 Conclusion

Based off the above ANSY results from Case 1 and 2, the Ti film is expected to maintain its structural integrity under normal operating conditions which are 7 pulses of beam unequally spaced in a 60 second window with the smallest possible window occurring with 7 pulses in 4 seconds depending on how the beam from LINAC is distributed to the MTA/ITA beamline. Case 2 validates the functionality of this window in MTA because when given 900 pulses of beam per minute the steady state temperature rise is on 3.3°C (room temp 22°C). Though the beam power is about 5431 W per pulse, the percentage of that power absorbed by the Ti window is η = 0.14% for every pulse. This results in a 7.7 W pulse which does not increase temperature of the film by an amount that would degrade the window's strength beyond what's allowable. Furthermore, transient thermal analysis was performed which showed that instantaneous local maximum temperatures due to 10 pulses of beam at 15 Hz were less than 4°C confirming that the strength of the window remains intact. Therefore, EN01668 is still valid under the conditions given in this note.

References

Incropera, F. P., Dewitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of Heat and Mass Transfer, Sixth Edition.* Hoboken, NJ: John Wiley & Sons, Inc.

Tanabashi, M. (2020, 03 31). *Particle Data Group*. Retrieved from http://pdg.lbl.gov: http://pdg.lbl.gov/2019/AtomicNuclearProperties/HTML/titanium_Ti.html

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